SOLAR SYSTEM STUDIES WITH SIRTF

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I. Summary

SIRTF will be a valuable tool for addressing a number of contemporary Solar System questions. Important advances in the study of debris disks, with or without entrained planets, around other stars will also be possible. The Solar System Working Group (SSWG) has identified three programs that appear suitable for Legacy Science surveys.

1. Core sample through the Solar System

A deep field survey of one square degree would give a "slice" through the Solar System from the asteroid belt to the Kuiper Belt, to study the size distribution of small asteroids, Trojan asteroids, comet trails, zodiacal cloud, Kuiper Belt planetesimals, and Oort Cloud comets.

2. Dust structures in the Solar System

IRAS revealed that the zodiacal dust cloud has considerable structure. SIRTF observations of the fine structure in carefully chosen directions will allow detailed modeling of the physical processes creating these dust structures. Moreover, accurate subtraction of the zodiacal emission is necessary to study faint diffuse radiation beyond the Solar System.

3. Dust disks around stars

Nearby systems can be imaged, yielding disk orientation, morphology and inner dust-depleted (planetary?) regions. A photometric survey of the ~200 G stars within 200 pc would allow measuring the SED, modeling the radial temperature distribution, thus dust size and spatial distribution, and determining properties vs. system age. Silicates, organics, and ices have key spectral features in the 10-100 μm spectrophotometry range.

Other important science includes the study of comets and observations of the major planets and their satellites. A particularly high priority is the study of Titan, surrounded by a nitrogen/methane atmosphere. At 20 μm, the surface may be detectable. Neptune's satellite Triton is time-variable in color, brightness, and near-IR spectrum and its ices can be studied spectroscopically by SIRTF.

Solar system observations present special requirements for SIRTF operation, not shared by observations of fixed sources. These include special geometry, tracking, and time criticality. Moreover, cool solar system objects can serve as calibration targets at long wavelengths. These requirements need to be considered during the design phase, in order that SIRTF can avoid certain difficulties experienced by other space observatories and maximize solar system science.

II. Introduction

The importance of the Space Infrared Telescope Facility to the study of Solar System bodies and phenomena, recognized since the initial definition of the SIRTF concept, is reaffirmed by a new appraisal of contemporary outstanding Solar System problems and the recently defined SIRTF system capabilities. Additionally, the great importance of SIRTF to the study of disk structures around other stars either with or without entrained planets, is reaffirmed.

The Solar System Working Group (SSWG) has examined the current status of a wide range of Solar System problems in light of modern insight, recent discoveries, the use of existing and projected large ground-based telescopes, and ISO, Galileo, and other space missions in progress or planned.

III. Legacy Science in the Solar System

The SSWG recognizes three programs that appear suitable for designation as Legacy Science. They have an interdisciplinary scope and will generate broad interest among scientists. Discoveries could lead to follow-on SIRTF observations.

A. Asteroids and Planetesimals -- A Core Sample Through the Solar System

Primitive solar system bodies -- the remnant planetesimals and their collisional products -- are spread throughout the solar system, from 2 AU to 100 AU and beyond. The largest members of the Kuiper belt family have only recently been detected. SIRTF can detect these primitive objects an order of magnitude smaller than previous surveys, allowing a fundamental census of the small solar system bodies.

A deep survey of 1 square degree near the ecliptic, with the proper geometry, will simultaneously sample several populations of these primitive bodies. By scheduling the survey fields at appropriate times, data on main-belt asteroids, asteroid dust bands, Trojan asteroids, comet trails, zodiacal cloud background and structure, Kuiper Belt planetesimals, and Oort Cloud comets will be obtained.

This survey needs to be carried out with IRAC and MIPS in close succession.

In addition to the solar system science, this Legacy Science project will provide data useful for assessing the "contamination" rate from asteroids in all IRAC and MIPS observations.

1. Main Belt asteroids

Most main belt asteroids are found between 2.2 and 3.4 AU from the sun and at ecliptic latitudes of less than 20 degrees. The size-frequency distribution of main-belt asteroids with diameters <10 km is essentially unknown. Yet the asteroid size distribution is important because it provides constraints on models of the original size distribution of the planetesimals formed in the inner solar system and their subsequent evolution. It is also an important datum in modeling the numerical size of the population of near-Earth asteroids and accounting for their evolution from the main belt into Earth-orbit-crossing orbits.

Visual magnitudes do not suffice for determination of asteroid sizes because of the unknown albedo. The absolute brightness of an asteroid depends on its cross section and albedo and asteroid albedos span a range of 0.02 to 0.5 -- a factor of 25. Moreover, there may be a systematic trend of albedo with size.

By observing thermal emission, and thereby avoiding the severe albedo bias present in any visual survey, an accurate picture of the distribution of asteroid diameters can be obtained. Consider two otherwise equal asteroids, one with an albedo of 0.02 and the other with an albedo of 0.5. The flux of reflected sunlight differs by a factor of 25 but the radiated flux at 15 microns differs by only a factor of 1.27.

By the end of the 1980s accurate sizes were known for about 2000 asteroids, mostly from IRAS data. Still, as noted above, this only provided reliable knowledge of the population with sizes above about 10 km. The IRAS survey was severely incomplete at the 1000 μJy level because at this flux level IRAS could only detect an asteroid in survey mode if its orbit was previously known. Too few asteroids with diameters less than 10 km had known orbits at the time of the IRAS mission. IRAS could "discover" asteroids in its pointed observation mode but few were found this way due primarily to the poor spatial resolution of its detectors.

A pending ISO program will sample about a one-quarter square degree region of the ecliptic to a 100 μJy flux limit at 12 microns and a 0.02 square degree region to a 10 μJy flux limit at 12 microns.

The SIRTF IRAC and MIPS instruments are capable of detecting asteroids down to sizes of a few hundred meters. (A 100 m main-belt asteroid has a flux density at 15 μm of about 10 μJy.) With IRAC it will be possible to sample a one square degree field down to 31 μJy at 8 μm while simultaneously obtaining images at 3.5, 4.5, and 6.3 μm in less than 100 hours. This has the advantage of simultaneously providing a reflected light photometric measurement (at 3.5 μm) and a thermal measurement (at 8 μm) which will allow the diameter to be directly calculated (once the asteroid's distance has been estimated). By following up these IRAC observations with MIPS observations, the 12 - 70 μm spectral energy distribution of the main belt asteroids can be determined and the outer solar system can be probed as well.

The fields of the MIPS 12 and 160 micron detectors are very narrow (0.5 arcmin) and it remains to be determined how best to combine them with the IRAC observations. One possibility is to obtain the IRAC observations immediately before the instrument change to the MIPS. In this way the overhead involved in using both instruments is reduced.

From these data it will be possible to determine the size-frequency distribution of asteroids with diameters greater than 1 km. Any region of sky along the ecliptic is suitable for this purpose.

2. Trojan asteroids

Jupiter Trojan asteroids will be detected along with main-belt asteroids as part of the survey described above, provided suitable regions of the ecliptic are chosen. (Observing on the ecliptic between 30 and 90 degrees elongation from Jupiter maximizes the chances of observing these objects.) Jupiter Trojans are transition objects between outer-main-belt asteroids and Kuiper Belt-cometary objects. Indeed some believe most Jupiter Trojans to be captured Kuiper Belt objects. SIRTF observations of these objects will provide physical evidence to test this hypothesis. If spectra and albedos of Jupiter Trojan asteroids prove to be similar to those of Kuiper Belt objects then this would be strong evidence that both classes of objects formed under similar conditions. This would enable studies to be made on these relatively near-by Kuiper Belt objects at signal/noise and resolutions impossible to obtain on their more distant cousins.

3. Kuiper Belt objects

The Kuiper Belt, located beyond the orbit of Neptune, has been shown by dynamical simulations to be an efficient source region for low- inclination short-period comets. It has been estimated that ~10^{10} comets populate the Kuiper Belt between 30 and 50 AU. A number of the largest Kuiper Belt objects have been detected in recent years. Assuming a typical cometary albedo of 4%, these objects have diameters in the range 100-350 km.

The mass density in the Kuiper Belt is puzzling. The present mass density does not appear to be sufficient for the comets to have accumulated.

[To be expanded]

4. The Oort cloud

[To be provided]

B. Dust Structures in the Solar System

All observations of the universe in the IR are veiled by a cloud of interplanetary dust particles (the zodiacal cloud) that permeates the inner and, possibly, the outer solar system. Thermal flux from these particles dominates the background signal in the mid-IR wavebands (12, 30, and 70 microns). IRAS and COBE produced large-scale maps of the zodiacal emission. In addition to the smoothly varying component, these data revealed that the cloud has spatial structure, including both dust bands due to asteroidal collisions and trails of cometary debris.

With its higher angular resolution and its vantage point away from the Earth, SIRTF presents a unique opportunity to investigate the spatial structure in the zodiacal cloud. There are several reasons why this study would be of astrophysical importance. Dust structures are the key to understanding physical processes -- the sources, sinks, and dynamical evolution of the interplanetary dust cloud. We also need to understand the solar system dust disk, as determined by planetary perturbations, in order to understand the structure of circumstellar dust disks that may contain unseen planets. Finally, models of the zodiacal emission incorporating the small-scale structure are necessary for accurate subtraction of the foreground emission in order to reveal faint extragalactic components, such as the remnant flux associated with the formation of galaxies.

The large scale structure of the cloud is determined by planetary perturbations. The plane of symmetry of the cloud is inclined to the ecliptic and slightly warped, and the Sun is offset from the center of rotational symmetry. Recently, it has been confirmed by COBE that the cloud has a marked trailing/leading asymmetry due to the trapping of dust particles in resonances with the planets, particularly the Earth.

Because of the resonant trapping of asteroidal dust particles, the Earth is embedded in a ring of dust that corotates with the Earth in its motion around the Sun. The Earth resides in a cavity in this ring and a cloud of dust permanently trails the Earth in its orbit. The number density of dust particles in this cloud peaks around 0.2 AU behind the Earth and is about 10% above the local background number density. Because of its heliocentric orbit behind the Earth, SIRTF has a unique opportunity to study the structure of this nearby cloud and thus to further our understanding not only of the zodiacal cloud but also the structure of other stellar disks that contain both dust and planets.

To determine the structure of the trailing cloud, the following MIPS observations are needed: (1) the ecliptic North and South poles at approximately weekly intervals, but not necessarily at the same time; and (2) in the ecliptic plane at an elongation angle of 90 degrees at approximately weekly intervals in the leading and trailing directions, but not necessarily at the same time. All of these observations would more useful if they were 2- to 3-degree scans taken in the "survey-while-scan" mode at 20 arcsec/sec.

Scans from +20 to -20 degrees ecliptic latitude at an elongation angle of 90 deg, in both the leading and trailing directions, are also needed. These scans would reveal the fine structure of the zodiacal cloud due to: (1) dust bands associated with Hungaria asteroid families, and (2) small incomplete dust bands and/or trails due to the comparatively recent breakup of asteroids in the 10-100 meter diameter range, or to small comets, or to large objects in the Kuiper belt. These scans would also observe many asteroids in the 1 km diameter size range and would help to determine the size-frequency distribution of the asteroidal population. They would also discover Kuiper Belt objects >100 km in diameter. These scans should be taken at six-month intervals to obtain parallax measurements of the fine structure.

If it is possible to observe with SIRTF outside the elongation range 64-120 degrees, then scans of the dust cloud from 120-180 degrees elongation would provide valuable information on the distant distribution of dust in the solar system, particularly dust in the asteroid belt associated with the dust bands.

C. Dust Disks Around Stars

The IRAS mission resulted in the startling discovery that main sequence stars often have disks of cool circumstellar grains with likely but not certain connection to planets. This possible connection can be explored by testing whether the Sun itself and other solar-type stars have circumstellar dust disks resembling the Vega and beta Pic systems. The best solar system analog in scale and morphology to the main sequence disks is the Kuiper Belt (KB) or Kuiper Disk, a zone of icy bodies in the ecliptic plane beyond the orbit of Neptune containing remnants of the solar system's formation. Cold dust in this region might evade detection from Earth because of strong emission from the warmer zodiacal dust in the inner solar system. Here we consider prospects for detection of solar system analogs around nearby stars by SIRTF.

A small-grain component of the Kuiper Disk can be compared with the Vega and beta Pic main sequence disks. The emission around these main sequence stars may arise from grains released by sublimation or collisions in a cloud of icy bodies similar to the KB. A model KB consistent with the observational data and with IRAS and COBE limits on a cold component of the zodiacal emission (Backman et al. 1995; the BDS95 model) has a grain population orbiting at r = 30-100 AU in equilibrium between various removal processes and replenishment by collisions of 0.3 M_{Earth} of 10 km-diameter comet nuclei (see also Stern 1995 for a KB collisional model). The BDS95 model predicts a fractional luminosity $\sim 10^{-7}$ relative to the Sun for our solar system's KB dust, that is $\sim < 10^{-2}$ and 10^{-4} of the values for the disks around Vega and beta Pic, respectively. Because the dust radiating area scales with the square of the total comet mass in a collisional model, the far-IR emission from these two stars can be approximately reproduced by similar KB models containing between 10 and 100 M_{Earth} of comets in the same radial zone.

SIRTF will have the capability to detect KB analogs around nearby solar-type stars and to survey a sample of A-type stars within 100 pc for disks similar to beta Pictoris.

Although considerable information can be obtained from photometry and spectrophotometry of circumstellar material, there will be a great premium on imaging those systems which are close enough to be resolved spatially. Imaging of the debris disks will require measurements which have both high sensitivity and can cope with the emission from the central star that in many cases dominates the integrated radiation of the entire system.

Model calculations for several stars with disks (beta Pic, tau Cet, 82 Eri, alpha Cen A) show that in each case the predicted surface brightness of the disk emission is well above the SIRTF sensitivity level. The beta Pic disk is of course considerably brighter than the star at 30 μm, and imaging with SIRTF's 2.4-arcsec pixels at this wavelength should trace the disk and its central cavity right into the position of the star. A solar-type disk around 82 Eri would be detectable with no subtraction of the stellar image and would stand out dramatically if the star were subtractable just to the 10% level. The high sensitivity and sharp, stable 70 μm images of SIRTF (that will be diffraction-limited at this wavelength), as well as the fine spatial sampling available with SIRTFs 4.8-arcsec pixels at 70 μm, will make subtraction of the stellar image possible to this level and probably better. Solar-type disks about alpha Cen A and tau Cet would be readily detectable at 70 μm if the star can be subtracted to 2%. The solar-type disk may also be detectable around alpha Cen A at 160 μm, but at long wavelengths the nominal SIRTF detection limit will be degraded by confusion noise.

Only a modest number of dust systems will be suitable for imaging studies with SIRTF, but many more will be observable photometrically. The structure of those systems which are measured photometrically but not imaged can be inferred from a model fit to the spectral energy distribution, as has been done to demonstrate the central sparse regions in the beta Pic and Vega disks. Such a model must contain a number of assumptions about grain size, composition, radial distribution, disk geometry, etc. Detailed imaging and spectroscopic studies of the nearest systems from ISO and SIRTF will be of particular importance for providing general verification of these assumptions and thereby greatly increasing the confidence with which the photometry and spectroscopy of distant, unresolved systems can be interpreted.

SIRTF will be capable of spectrophotometric measurements from shortward of 10 to about 100 μm with resolution R~20-50. Spectrophotometry will be of value not only for determining the composition of circumstellar material but also to help establish small but systematic deviations from the expected photospheric flux which would signal the presence of emission from circumstellar dust.

There would be three principal tasks in low-resolution (R~50) spectrophotometric studies of main sequence stellar dust disks in order of increasing difficulty and information gained about disk composition. First, a spectrum with S/N ~ 10 permits some modeling of the radial temperature profile of the disk, assuming nothing about the circumstellar material except that the disk is optically thin and individual grains are blackbodies. Second, a spectrum with S/N~30 allows refinement of optical depth and temperature profiles on the assumption that the circumstellar material belongs to some general group of minerals. Silicate dust, for example, has a strong emission feature between 7 and 15 μm and weaker features between 18 and 40 μm. Finally, a spectrum with S/N~100 permits detailed comparison of spectra to specific minerals, such as olivine.

Ground-based spectra of beta Pic show overall similarities to the emission from cometary grains (at 11 μm), which in turn resemble the spectra of interplanetary dust particles (IDP). IDP spectra are identified with emission from olivine, a mafic crystaline mineral found in silica-poor terrestrial rocks and in meteorites. Olivine also has diagnostic spectral structure in the 18-40 μm region. Water ice also has diagnostic spectral features in the SIRTF spectral region; the presence and amount of water ice in KB-like systems around other stars is of particular interest because of the role of comets in bringing water to the earth, a critical step in making a habitable planet. Ice can be identified through a broad spectral feature near 65 μm, a wavelength at which the contrast of a cool, icy debris system to the central star will be favorable. SIRTF will have the ability to take low-resolution far-IR spectra from 50 to 100 μm to study this feature.

Comparison of the properties of systems around nearby stars with those of our solar system will help make a connection between dust disks and planets. For example, it is important in relation to planets to find how the dust density and characteristic temperature (dominant location) evolve with stellar age as a clue to what is happening to the dust source planetesimals. Although IRAS has apparently discovered systems ranging in age from some which have just emerged from their parental dust clouds (~Myr) to others approaching the age of the solar system, we do not have enough systems of intermediate age to understand disk evolution and the ultimate fate of the planetesimal population. ISO will make substantial progress in this area by studies of young cluster stars. Field star ages will be much better known soon via HIPPARCOS parallaxes and improved calculations of isochrones. These ages combined with photometry of field star disks from ISO and SIRTF will provide an excellent sample for evolutionary study.

The fact that the minimum estimated mass for the beta Pic disk is ~0.1 M_{Earth} indicates that a grain distribution with as little total mass as 1% of the solid mass of the planets in our system can be easily detected in the mid- and far-IR. This corresponds to the amount of interplanetary material estimated to have been present a few tenths of a Gyr after the formation of the Sun during the long final stages of planetary construction. If systems with ages corresponding to our solar system's epoch of planet formation are found by ISO and SIRTF to have both warm (terrestrial) and cool (Jovian-to-KB) dust, but the warmer dust mostly disappears leaving only KBs as persistent remnants, a solid connection to the history and present state of our solar system would be established.

In summary, a Legacy Project would include:

(1) Imaging of the few brightest nearby systems
(2) Survey of the ~200 solar-type stars within 20 pc to detect a disk comparable to the Kuiper Belt

(3) Survey of a sample of the ~2000 A stars within 100 pc to detect beta-Pictoris type disks.

IV. Other Solar System Programs

A. Studies of the Major Planets and their Satellites

1. Planets

Observations of the major planets will have been conducted by the ISO investigation teams over the same spectral range and usually with much higher resolution than is available to the nominal SIRTF instrument configuration. For the most part, these bodies are not particularly dim or difficult to observe; thus, there are few advantages which SIRTF presents to make advances in the knowledge of the chemistry or the physical forces acting in these bodies, assuming a fully successful ISO mission.

There are exceptions to this generalization, and there are good reasons for measuring the major planets. The primary exceptions are the planetary spectra of Uranus and Neptune, which are extremely faint. These include the entire short-wavelength thermal region, somewhere between 4 and 15 μm. It is here, between emissions of C_2H_6 at 12 μm and CH_4 at 7 μm (known for Neptune, possible for Uranus) in which a definition of the continuum is possible or deviations from a continuum might be noted. The continuum itself will be constituted by the collision-induced absorption spectrum of H_2 and can be used to determine the temperature, confirm the He mixing ratio, define the global ortho/para H_2 ratio, or to seek other continuum absorption or scattering arising from gases or particulates. For example, it may be possible to observe C_2H_4 arising from a fainter continuum near 10 μm in Neptune's spectrum.

Measuring the brighter bodies, such as Jupiter and Saturn, will help to check the consistency of the calibration scheme. The calibration of ISO's LWS instrument is based on an atmospheric model for Uranus, tied both to Voyager IRIS and to ground-based far-IR and submillimeter results. Independent cross checks of the spectra of Jupiter, Saturn, Uranus, and Neptune will establish the consistency of the various Voyager IRIS observational results for the whole-disk thermal output. A question arises in these circumstances as to whether the dynamic range of the spectrometer on SIRTF can accommodate the thermal output of Jupiter and Saturn.

The known temporal variability of Neptune, even at whole-disk resolution, provides another reason to observe its atmosphere at time intervals separated by several hours to several months. Disk-integrated photometry of Neptune at wavelengths longward of 15 microns is sensitive to temperature changes alone, between 8 and 14 microns to temperatures and hydrocarbon abundances, and at shorter wavelengths to temperatures and cloud properties. It will be useful, when variability of the whole-disk spectrum is noted, to determine the correlation between thermal, cloud and compositional variability.

If a cross-correlation between the ISO and SIRTF photometric data can be established, then the baseline of whole-disk photometry and radiometry can be extended over many years.

Whole-disk photometry and radiometry of Uranus as a function of time will also be worthwhile, because of the slow rotation of Uranus' axis toward a configuration perpendicular to the Earth by 2006-2007. Observations during this configuration, compared to previous photometry and radiometry, will be particularly useful to determine the meridional (N-S) and zonal (E-W) average temperatures, cloud characteristics, and possibly the distribution of certain atmospheric gases. The spectrum would be sampled annually, in order to search for slow, rotationally dependent changes.

Spectroscopy of Mars will also help to confirm the distribution of water across its surface and determine its temporal variability on a global scale. Furthermore, the observations of spectral characteristcs of astmospheric dust, particularly in epochs of global dust storms, will help identify characteristics of the scattering/absorption properties of the dust particles and their vertical distribution. Again, the issue of dynamic range in the IRS arises for observations of a bright source such as Mars.

2. Major Planet Satellites

At a particular high priority is the observation of Titan, which is surrounded by an N_2 and CH_4 atmosphere. Titan's atmosphere will be the subject of intensive investigation by the Cassini spacecraft and the Huygens probe in a time frame subsequent to the nominal SIRTF mission. At 20 μm, Titan's atmosphere may be sufficiently transparent to permit the thermal radiation of the surface to be detected. Thus, correlations between Titan's 20-μm flux and its orbital phase may provide some useful information on the product of the variability of its surface emissivity and its topography which should reflect the near-adiabatic conditions of its lower atmosphere and the consequent temperature lapse rate near the surface, wherever that local surface may lie.

Neptune's satellite Triton is known to be time-variable in its photovisual color, global brightness, and near-infrared spectrum. These variations probably arise from a combination of Triton's internal geological activity and the response of the frozen volatile ices (N_2, CH_4, CO, H_2O) on its surface to the seasonal extremes induced by its peculiar orbital geometry. Spectroscopy of Triton with the IRS at each six-month opportunity throughout the SIRTF mission will help build upon the ground-based and Voyager observations that have shown Triton to be a variable object, and eventually will guide modeling studies of the nature of this important planetary satellite.

B. Comets

Comets are the best probes into the origin and early history of the solar system. The chemistry of comets reveals the composition of protosolar materials and the pathways of their evolution from the precursor molecular cloud into the solar system bodies.

Knowledge of the present physical state of cometary nuclei and comae is necessary for assessing the extent of possible transformations that had occurred since the time of comet's formation. Studies of comets also are related to exobiology since comets bear the evidence of prebiotic organic chemical evolution under interstellar and nebular conditions, and delivered significant quantities of organic compounds to the terrestrial planets.

We consider several aspects of the study of comets with SIRTF; active comets relatively near the Sun (< 3 AU), icy grains, inactive or episodically active comets at large heliocentric distance including the Centaur objects, compositional links of comets with interstellar grains, and the study of Comet Wirtannen in suport of the Rosetta mission. SIRTF observations of comets as targets of opportunity are discussed in the report of another working group.

1. Active Comets

Active comets are surrounded by a coma of gas and dust emitted from the nucleus. Ground-based infrared observations of comets have concentrated on the interesting 3 μm region, where many organic species have spectral features, and the 10 μm region, where strong emission from silicate grains is frequently seen. The spectral region beyond 20 μm is relatively unexplored.

SIRTF IRS spectra at wavelengths < 40 μm and the lower resolution MIPS spectra at lambda 50-100 μm have the potential for detecting new spectral features arising from solid grains. Crystalline olivine has several peaks between 20 and 40 μm and these should be visible in comets displaying the 11.2 μm peak ascribed to crystalline olivine. Carbon-rich astronomical sources can have a distinct emission feature at 21 μm and strong, broad 30 μm emission. Water ice has bands at 40-70 μm, but these are best searched for in comets farther from the sun, as described below. The ISO SWS discovered strong emission features at 16-35 μm arising from crystalline olivine in the spectrum of comet Hale-Bopp, an unusually active comet with an unusually high abundance of small (submicron) grains. This spectrum is remarkably similar to the SWS spectrum of HD100546, a late Herbig Ae/Be star, in transition to a beta Pictoris object. The similarity between these spectra establishes a possible link between the primordial solar system dust preserved in comets and the dust around young stars. It is possible that the grains surrounding HD100546 have been released by cometary bodies colliding with the central star.

The spectral energy distribution of the dust thermal emission from 12-160 μm allows one to discriminate between large and small grains, because the micron-sized grains usually responsible for the 10 μm thermal emission from comets cannot radiate efficiently at 70 and 160 μm. Thus, images with MIPS at 12, 70, and 160 μm can trace the spatial distribution of large versus small grains in the coma.

It is desirable to collect data on a large sample of comets of dynamically different types: Jupiter-family (orbital period T of 6-7 years), Halley-family (T < 200 years), long-period comets (T > 200 years) and new comets (first entrance into the inner solar system). Composition and properties may be different for objects of different classes reflecting varying conditions and temperatures of their formation (i.e. the giant planet subnebulae or the Uranus-Neptune zone or the Kuiper belt) and their subsequent evolution. There are more than 200 periodic comets with known orbits from which to select suitable objects, based on the SIRTF launch date and its operational lifetime. The rate of discoveries of bright long-period and new comets is on the order of 1-2 objects per year. Time should be set aside for observing these comets as targets of opportunity as soon as they are discovered.

2. Icy Grains

Comets are thought to consist of 40% or more of water ice, presumably formed at low temperature (< 50 K). This ice, with trapped impurities (CO, CO_2, HCN, CH_3OH, etc.), initially is most likely amorphous, but would gradually convert to the cubic crystalline form when the material is heated above 148 K during a comet's approach to the Sun. The exothermic transition reaction would supply additional energy to the cometary ice, thus playing a crucial role in cometary physics and chemistry. For example, the amorphous-crystalline ice transition influences the thermal conductivity and diffusion properties of the ice and the release of trapped volatiles, and may be responsible for cometary outbursts or the anomalously bright behavior at large heliocentric distances.

Water ice has wide emission bands between 40 and 70 μm indicative of the crystalline phase of the ice. The state of water ice in comets tests models of cometary interiors and the conditions of cometary nuclei accretion. These bands have never been seen in a comet. SIRTF will provide the opportunity to search for these bands in comets beyond ~3.5 AU, where icy grains would be stable against sublimation. Observations of cold grains in the cometary coma before they are heated is a clue to recovering the original, unaltered composition of the cometary material.

Other organic ices (i.e. methanol ice) also have never been directly observed, but are abundant in the interstellar medium and might be present in cometary grains at large heliocentric distances. They would evaporate and/or undergo chemical transformation closer to the Sun, thus giving rise to extended sources of some gaseous cometary species. Direct observations of organic ices in the coma of a distant comet would permit a comparison of cometary and interstellar ices, which is essential for determining the chemical origin of comets.

3. Observation of Comets at Large Heliocentric Distances

For comets in which activity ceases at large heliocentric distances thermal measurements can yield the diameter, shape, and albedo of the nucleus. Since some comets are very slow to return to a quiescent stage, one must observe them at extreme distances to have any hope of seeing the bare nucleus. With SIRTF, for example, it will be possible to measure the bare nucleus of Halley at aphelion with less than a day's integration. Non-detection at the very faint limits of SIRTF can establish very strict upper limits to the sizes of comet nuclei, of particular value for comets that show a high state of activity near the Sun.

Some comets are active at heliocentric distances too great for water to sublime. Comets such as Schuster (1975 II) and P/Schwassmann-Wachmann 1 never reach the water sublimation limit, but show strong activity and repeated outbursts. The new comets Bowell and Stearns and long period comet Hale-Bopp were active preperhelion beyond the orbit of Jupiter. Halley was observed to have a burst of activity post-perhelion at 14 AU. A possibly new class of cometary objects beyond Saturn has been discovered -- the Centaurs, with Pholus and Chiron the first members. Chiron has shown comet-like behavior at heliocentric distances greater than 10 AU.

These observations raise a number of issues. What is the nature of cometary activity at large heliocentric distances? Is it driven by real-time surface processes, lagged thermal sublimation or other phase changes of material within the nucleus, or is it a result of non-thermal processes? Would some level of activity at large heliocentric distances be seen for most comets? Is this form of activity related to the comets age? The high sensitivity of SIRTF to the thermal emission from cometary dust allows thermal images to be obtained at large distances and subsequent analysis of the morphology and content of the dust coma.

A program of monitoring known comets at large heliocentric distances will yield valuable science, with the objectives of characterizing the nucleus of non-active comets, studying the mechanisms and frequency of distant activity, and searching for the 40-70 μm bands of water ice.

4. Comet Wirtanen and the International Rosetta Mission

The Rosetta comet orbiter/lander mission will be launched in 2003 to rendezvous with comet Wirtanen in 2011. The launch of SIRTF with its extensive IR imaging and spectroscopy capabilities offers a unique opportunity to study the Rosetta mission target from 2002-2004. These 3 years represent the same portion of Wirtanen's orbit that Rosetta will fly with the comet some 10 years later. More explicitly, SIRTF has the opportunity to develop a remote sensing database on the comet's IR characteristics, coma activity, and thermal properties that can both serve as a precursor database that will improve our ability to plan detailed observation sequences with Rosetta, and provide a "big picture view" that will be invaluable for the interpretation of Rosetta data.

Ideally, SIRTF observations would be made with IRAC, MIPS, and the IRS about once per week during each ~40 day observing window during the SIRTF mission. In toto, this would provide ~25 snapshots of Wirtanen's coma and nucleus as it transitions from a bare, essentially inactive nucleus, through the onset of activity, and then to perihelion (at ~1.1 AU) in 2004.

When the comet is inactive, MIPS and IRS can measure the SED and compositional characteristics of the nucleus, for which no information is presently available. Once the comet becomes active, the IRS should study the composition of the coma and its dust. IRAC and MIPS should image the developing dust structures. The 70 and 160 μm images will trace the spatial distribution of relatively large dust particles, an important consideration for the navigation of the spacecraft. For reference, when the comet is 1 AU from the Earth in 2003, IRAC's 5 arcmin field of view will comprise a linear scale of ~$2x10^5$ km, which is comparable to parent molecule scale lengths against dissociation.

V. Operational Issues

Solar system observations present special requirements not shared by observations of fixed sources, including special geometry, tracking, calibration, and time-criticality. By considering these requirements during the design phase, the SSWG hopes that SIRTF can avoid certain difficulties experienced by other space observatories and optimize solar system science.

A. Tracking moving targets

Comments based on the experience with the Hubble Space Telescope in tracking solar system bodies:

- Most targets observed with HST have had angular motions of 0.1 arcsec/sec or less. Thus, the current specification for tracking with SIRTF should satisfy most observation scenarios. However, near-Earth asteroids such as 4179 Toutatis and comets such as Hyakutake can have significantly higher rates (of order 1 arcsec/sec). Such tagets offer unique observational opportunities and it would be valuable to allow tracking at higher rates even with reduced tracking precision.

- A serious limitation of HST capabilities arose because the tracking command used for small angle maneuvers such as peak-ups could not be used while the spacecraft was tracking a moving target. This has required inefficient workarounds on HST. For SIRTF, we should ensure that peak-ups, slews between apertures, and nodding are all possible for both fixed and moving targets.

- Additional overheads are required for HST moving target observations. The overheads to start and stop tracking are small. A more significant limitation is caused by a limit of instrument overheads. This situation should be avoided for SIRTF.

- The possibility that a guide star will move out of the field of view of the star trackers during a moving target observation will need to be considered. On HST this can cause a failure of the observation.

B. Faster Tracking Rate with (possible) Degraded Performance

In order to take advantage of the unique observing opportunity for an Earth-approaching comet or asteroid, a tracking rate for moving objects that is greater than the maximum nominal value is important. Even if the precision of the tracking at the increased rate is degraded, it would be of great use for a particularly important target of opportunity.

The SSWG requests that the Project consider providing a tracking rate greater than the maximum nominal (by approximately a factor of two), and evaluate the possible performance degradation.

C. Scheduling

Comments based on scheduling the Hubble Space Telescope for solar system observations:

- A significant challenge for HST is the uncertainty in when observations will execute on orbit. For HST this is caused by the inability to accurately predict HST orbit events to better than a few minutes accuracy a month in advance when scheduling sequences are planned. The resulting time uncertainty translates into a positional uncertainty for moving targets that can be significant. For SIRTF, consideration of flexibile scheduling will have to build in a mechanism to allow appropriate target positions to be used.

- Some comets and asteroids, especially Earth approachers, can have significantly uncertain ephemerides. On HST this problem is handled by allowing uplinked offsets to the target ephemerides that have been loaded onboard. A better solution for SIRTF would be to allow complete new target ephemerides to be uploaded at any time prior to observations.

D. Use of Quad Sensor or Star Tracker for Science Data

The SSWG identifies a need for simultaneous visible wavelength photometry (to within ±5% precision, approximately) of sources for which infrared photometric or spectroscopic data are obtained. This is particularly useful for objects, such as asteroids and comets, which change brightness rapidly and for which the interpretation of the IR data depend upon the simultaneous visible flux.

The SSWG requests the Project to investigate options for data acquisition with the star tracker, or perhaps more effectively, the quad sensor.

E. Off-Nominal Pointing Constraints

Because many solar system phenomena are time-critical and the objects are usually best observed near opposition (180 deg. from the Sun), the nominal SIRTF pointing capabilities are too constraining to make full use of the facility for solar system observations.

The SSWG requests that the Project expand the range of angles away from the Sun at which the facility may be used to include 180 deg, and establish an on-target time (exclusive of slewing and settling) at that elongation of one hour.

The needs of the SSWG for this expanded capability lie in parallel with the needs of the Target-of-Opportunity group.

Short of gaining this capability, the SWG urges the Project to maximize and optimize the power constrained viewing zone with the needs of solar system observers in mind.

F. Calibration Plan

The SSWG has identified the need for absolute flux calibrations of various SIRTF instruments with which solar system observations will be made. While each instrument will have its own calibration plans and special needs, the need for a system-wide calibration scheme and/or plan should be investigated. A link to the ISO flux calibration is very desirable, in order to provide long-baseline studies of temporal variation for the outer planets.

Cool solar system objects, such as asteroids, Uranus, or outer planet satellites, may be suitable SIRTF calibration sources. Close collaboration with solar system astronomers is essential to ensure that the long wavelength fluxes from these objects are properly understood.

The SSWG recommends that a Working Group be formed to develop a full system Calibration Plan for SIRTF.